

METHOD AND APPARATUS FOR
CORRECTING FOR SYSTEMATIC ERRORS IN
TIMING PATTERN GENERATION

This application is a continuation-in-part
5 application of co-pending, commonly assigned
Application Serial No. 08/628,910, filed April 08,
1996, which is a divisional application of
Application Serial No. 08/348,773, filed December 01,
1994, now abandoned. Application Serial No.
10 08/628,910 is hereby incorporated herein by reference
in its entirety.

CROSS REFERENCE TO RELATED APPLICATIONS

This application is related to United States
Patent No. 5,485,322 of T. Chainer et al. issued on
15 January 16, 1996 entitled, "Method and System for
Writing a Clock Track on a Storage Medium", which is
a divisional application of Application Serial No.
08/028,044, filed March 08, 1993, now abandoned.
U.S. Patent No. 5,485,322 is commonly assigned
20 herewith, and hereby incorporated herein by reference
in its entirety. It is also related to United States
Patent No. 5,612,833 of E. Yarmchuk et. al., Attorney
Docket No. Y0994-253A, issued on March 18, 1997
entitled, "Radial Self-Propagation Pattern Generation
25 for Disk File Servowriting," which is also hereby
incorporated herein by reference in its entirety.

TECHNICAL FIELD

The invention relates generally to hard disk
drive memory storage devices for computers. More
30 particularly, it relates to disk drive apparatus and

-2-

to a method for writing servotrack information therein. More specifically it relates to alleviating the need for a complex mechanical and/or optical positioning system to establish servopatterns on the recording surfaces of the recording media.

BACKGROUND ART

Increased levels of storage capacity in floppy and hard disk drives are a direct result of the higher track densities possible with voice-coil and other types of servo positioners, as well as the ability to read and write narrower tracks by using, for example, magnetoresistive (MR) head technology. Previously, low track density disk drives were able to achieve satisfactory head positioning with leadscrew and stepper motor mechanisms. However, when track densities become so great that the mechanical error of a leadscrew stepper motor combination is significant compared to track-to-track spacing, an embedded servo is needed so that the position of the head can be determined from the signals it reads.

Conventional servo-patterns (also referred to as servo-data) typically include short bursts of a constant frequency signal, very precisely located offset from a data track's center line, on either side. The bursts are written in a sector header area, and can be used to find the center line of a track. Staying on center is desired during both reading and writing. Since there can be sixty, or even more, sectors per track, that same number of servo-data areas must be dispersed around a data

-3-

track. These servo-data areas allow a head to follow a track center line around a disk, even when the track is out of round, as can occur with spindle wobble, disk slip and/or thermal expansion. As
5 technology advances to provide smaller disk drives, and increased track densities, the placement of servo-data must also be proportionately more accurate.

One example of servo-data is shown in FIG. 1,
10 which includes a sector header 2 followed by a pattern to provide radial position information. The sector header includes a Servo ID (SID) Field 4 and a Grey Code Field 6, which require precise alignment track to track. Misalignment in these patterns
15 results in destructive interference of the magnetic pattern and reduces the amplitude of the signal which leads to errors. Specifications on the alignment in modern disk drives is approximately 25 nanosec (3 sigma) track to track for a disk rotation period of
20 roughly 11 milliseconds or 2.3 ppm. This narrow time window therefore requires precise measurement of the disk angular position over many revolutions of the disk.

As disk drives become smaller and track
25 densities increase, there is a desire to reduce the size of the servo-data areas, such that they take up less space on the disk. In order to reduce the size, however, the servo-data are written at higher and higher frequencies. These higher frequencies require
30 tighter timing tolerances from track to track.

-4-

In one example, timing is provided by writing trigger patterns at various locations of the disk. It is understood that in writing a trigger pattern a specified time after a trigger, the presence of electronic delays in the trigger and write circuitry is taken into consideration. This is described in IBM Technical Disclosure Bulletin, Vol. 33, No. 5 (October 1990), where the delay between A and B clock areas is measured and stored. This delay value is used to advance the write timing of all subsequent servo-tracks and clock areas.

Although, the IBM Technical Disclosure Bulletin, Vol. 33, No. 5 (October 1990) discussed the presence of electronic delays, it did not discuss how to achieve optimum track to track trigger pattern alignment in the presence of systematic errors (e.g., constant for every sector), which vary as a function of radial position and/or circumferentially in the propagation process.

Therefore, a need still exists for a capability to reduce systematic errors in the writing of timing patterns. In particular, a need exists for an improved capability to:

- 1) Eliminate a varying systematic error when the recording head has spatially separate read and write elements, such as is the case for magnetoresistive heads. This results in a read to write time delay which is radially dependent.

-5-

- 5 2) Remove the varying systematic error due to
 'a read element and write element, which are
 non-parallel, resulting in an error in the
 measurement and subsequent writing of
 trigger patterns.
- 10 3) Eliminate servo pattern rotation due to
 residual or unmeasured systematic errors by
 using a once per revolution clock index
 derived from the motor drive current
 waveform or any other sensor.
- 4) Reduce systematic errors which vary
 circumferentially.
- 15 5) Minimize the error due to a recording head
 mounted non-parallel to the actuator
 motion.

SUMMARY OF THE INVENTION

20 The shortcomings of the prior art are overcome
 and additional advantages are provided through the
 provision of a method and apparatus for correcting
 for systematic errors in the writing of timing
 patterns on a storage medium of a storage device.

25 In one example, a time interval is measured
 between a trigger pattern written at a first radial
 position of the storage medium and a rotational
 index. The rotational index is related to the
 rotational orientation of the storage medium with
 respect to a fixed frame of the storage device.
 Further, the location of another trigger pattern to

-6-

be written is shifted. The measured time interval is used in determining the shift in location of the another trigger pattern.

5 In another embodiment of the invention, a method and apparatus for correcting for systematic errors in the writing of timing patterns on a storage medium of a storage device are provided. The method includes, for instance, determining a systematic delay for use in writing at least one trigger pattern at one radial
10 position of the storage medium, and updating the systematic delay for use in writing at least one trigger pattern at another radial position of the storage medium. The updated systematic delay is different from the systematic delay for use in
15 writing at the one radial location.

In another aspect of the present invention, a method and apparatus for correcting for systematic errors during self-servowriting of a storage device are provided. In one example, a systematic error is
20 measured at a plurality of predetermined radial positions, wherein a measured systematic error for each of the plurality of predetermined radial positions having a mean whose absolute value is greater than zero is determined. Each of the
25 measured systematic errors is corrected in order to reduce the measured systematic errors.

In yet a further embodiment of the present invention, a method and apparatus for self-servowriting a storage medium in a storage device
30 including a head positioned for interaction with the storage medium are provided. In one example, the

-7-

method includes writing a first set of trigger patterns on a first track of the storage medium; determining a read to write time delay; determining an index correction value; determining at least one
5 random error correction value; computing a set of delay values which are a function of the read to write time delay, the index correction value and the at least one random error correction value; and triggering from the first set of trigger patterns and
10 writing a second set of trigger patterns on a subsequent track using the set of delay values.

In another embodiment of the present invention, a method and apparatus for correcting for systematic errors in the writing of timing patterns on a storage
15 medium by a head of a storage device are provided. The method includes, for instance, detecting one or more circumferential systematic errors and correcting for the one or more circumferential systematic errors.

20 The present invention advantageously corrects for a varying systematic error, such as when the recording head has spatially separate read and write elements, such as is the case for magnetoresistive heads. Additionally, the varying systematic error
25 due to a read element and a write element, which are non-parallel, resulting in an error in the measurement and subsequent writing of trigger patterns, is reduced. Further, it reduces servo-pattern rotation due to residual or unmeasured
30 systematic errors by using a once per revolution clock index derived from the motor drive current waveform or any other sensor.

-8-

Additional features and advantages are realized through the techniques of the present invention. Other embodiments and aspects of the invention are described in detail herein and are considered a part
5 of the claimed invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The subject matter which is regarded as the invention is particularly pointed out and distinctly claimed in the claims at the conclusion of the
10 specification. The foregoing and other objects, features, and advantages of the invention will be apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

15 FIG. 1 illustrates a disk and a typical disk servo pattern;

FIG. 2a depicts one embodiment for writing timing marks on a disk surface;

20 FIG. 2b shows how independent casual paths of pattern propagation are generated and can be eliminated by measuring and by using an additional revolution of the disk;

25 FIGs. 3a-3c depict one example of a self-servowrite apparatus incorporating and using the capabilities of the present invention;

-9-

FIGs. 4a-4b show one example of how servo patterns are written with a dual revolution process;

5 FIGs. 5a-5c show how the physical separation of read and write elements results in a time delay;

10 FIGs. 6a-6b show how a non-parallel read/write head results in an apparent shift of the trigger pattern when the head is moved off track center;

FIG. 7a shows non-parallel read and write elements resulting in pattern rotation;

FIG. 7b shows a misaligned head mounting resulting in pattern rotation;

15 FIG. 8 shows the effect of systematic errors on pattern propagation;

20 FIG. 9 shows one example of a process to reduce systematic error and control pattern rotation, in accordance with the principles of the present invention;

25 FIG. 10 depicts one example of a block diagram of the processes used to reduce systematic and random errors in a pattern propagation process, in accordance with the principles of the present invention;

-10-

FIG. 11 is one embodiment of the start-up procedure shown in FIG. 10, used to initialize various variables to be used during the systematic and random error reduction process of the present invention;

FIG. 12 depicts one embodiment of the logic used to measure intervals at TP_i , in accordance with the principles of the present invention;

FIG. 13 depicts one embodiment of the read procedure depicted in FIG. 10, in accordance with the principles of the present invention;

FIG. 14 depicts one embodiment of the logic used to measure and update an index estimate, in accordance with the principles of the present invention;

FIG. 15 depicts one embodiment of the logic used to correct measured intervals, in accordance with the principles of the present invention;

FIG. 16 depicts one embodiment of the logic used to compute algorithm corrections and target intervals, in accordance with the principles of the present invention;

FIG. 17 depicts one embodiment of the logic used in the step procedure depicted in FIG. 10, in accordance with the principles of the present invention;

-11-

FIG. 18 depicts one embodiment of the logic used during the write procedure of FIG. 10, in accordance with the principles of the present invention;

5 FIG. 19 shows one example of a technique to remove the effects of spindle velocity jitter, in accordance with the principles of the present invention;

10 FIGS. 20a-20b show examples of a technique of clock propagation with reduced interval jitter, in accordance with the principles of the present invention;

15 FIG. 21 shows one example of a technique of clock propagation without incurring an additional revolution of the disk, in accordance with the principles of the present invention;

20 FIG. 22 shows one example of how servo patterns are written with a single revolution clock propagation process, in accordance with the principles of the present invention; and

FIG. 23 depicts one example of a hardware technique to detect trigger patterns written on a disk, in accordance with the principles of the present invention.

-12-

BEST MODE FOR CARRYING OUT THE INVENTIONSELF-SERVOWRITER OVERVIEW

One embodiment of a self-servowrite apparatus incorporating and using the capabilities of the present invention is shown in FIGs. 3a-3c, and described in detail below.

Referring to FIG. 3a, in one example, a self-servowrite apparatus 300 interfaces to, for instance, a storage device 302 (such as, for instance, a disk storage device). In one embodiment, the storage device includes a recording head or transducer 304, which writes information to and/or reads information from one or more storage medium 306 (referred to herein as storage media). The storage medium rotates via a motor 312 located within storage device 302.

Transducer 304 is coupled to an actuator 308, used in moving the transducer radially along the storage media. Transducer 304 receives its signals from a voice coil motor 310 coupled thereto.

The storage device is coupled to self-servowrite apparatus 300, as described in further detail herein. In one example, self-servowrite apparatus 300 includes a PC controller 314, a radial propagation controller 316, a timing propagation controller 318, a pattern generator 320, a motor controller 322 and a read/write interface card 324, each of which is described below.

-13-

PC controller 314 is a standard personal computer (such as, for instance, an Aptiva Model 2176 offered by International Business Machines Corporation) coupled to other components of the system via a system bus 315. In one example, the system bus conforms to ISA standards and enables communication among the PC controller and the other system components, as well as between the components themselves. The bus allows addressing and control of the other components by the PC controller. In particular, the controller is controlling the components on a sector by sector basis during the technique of the present invention. In another example, the bus can be eliminated and each of the components can communicate directly.

Coupled to bus 315 is radial propagation controller 316, which is used to control the writing of radial propagation bursts (described below) on storage medium 306. In particular, the radial propagation controller reads the propagation bursts along a track on the storage media to position the transducer to write subsequent propagation bursts on a next track.

One example of a radial propagation controller is described with reference to FIG. 3b. In one example, radial propagation controller 316 includes an amplitude demodulator 330, which receives as input readback signals from read/write interface card 324. The read/write interface card receives the signals from recording transducer 304. The amplitude demodulator converts the readback signals to a position signal, which is input to an analog/digital

-14-

(A/D) converter 332. The converter converts the signal to digital and passes the signal to a processor 334 (e.g., a digital processor, such as a TMS 320 offered by Texas Instruments).

5 The processor calculates the error in the present head position from the desired position and outputs a correction value to a digital to analog converter (DAC) 336. DAC 336 converts the correction value into an analog signal, which is input to a
10 voice coil motor (VCM) driver 338. The VCM driver converts the analog voltage signal into a current, which drives actuator 308 to move transducer 304.

 Returning to FIG. 3a, timing propagation controller 318 is also coupled to system bus 315.
15 The timing propagation controller controls the writing of trigger patterns (described below) on a given track. In particular, it reads trigger patterns on one track and writes subsequent trigger patterns on a next track.

20 One example of a timing propagation controller is described with reference to FIG. 3c. In one example, timing propagation controller 318 includes a trigger pattern detector 340, a time interval analyzer 342, a processor 344, one or more memory
25 units 345 coupled to processor 344, a trigger pattern window 346 and a programmable delay 348, each of which is described below.

 Input to trigger pattern detector 340 are readback trigger patterns output from read/write
30 interface card 324. Detector 340 converts the

-15-

readback trigger patterns into a digital signal,
which is input to time interval analyzer 342.

Time interval analyzer 342 precisely measures
the time between trigger patterns. In one example,
5 time interval analyzer 342 is a HP 5372A. The
measured time is output from analyzer 342 and input
into processor 344.

In one example, processor 344 is a digital
processor (e.g., a TMS 320 offered by Texas
10 Instruments), which stores the information received
from analyzer 342, as well as other components of
controller 318. Processor 344 includes the logic
used to perform many of the calculations and
determinations used in the present invention, as
15 described below with reference to the flow diagrams.
For example, the processor is used to calculate a
delay value used to shift the location of a
subsequent pattern generator output to write a
trigger pattern.

20 In one example, the processor controls the
opening of trigger pattern window 346 at a desired
time, which enables the trigger pattern detector at
the desired times, such that the incidences of false
triggers are reduced.

25 In addition to the above, controller 318
includes programmable delay 348, which receives its
input from processor 344. Processor 344 uses the
time measurements provided by time analyzer 342 to
calculate a shift value, which is input to
30 programmable delay 348. The shift value is used to

-16-

shift the writing of the product servo-patterns. The programmable delay provides the shifted signals (e.g., in time) to pattern generator 320.

An input to processor 344 is motor index 323.
5 In particular, the motor index is input to a counter 349 within the processor. The counter measures the time between the index and a first trigger pattern. When the motor index comes in, the counter starts counting until the next trigger pattern is detected.

10 Referring back to FIG. 3a, the system also includes pattern generator 320, used to write patterns and to store them in its memory. It is capable of writing various patterns, such as, for instance, radial propagation burst patterns, trigger
15 patterns and/or product servo-patterns, which are described below.

The radial propagation burst patterns provide radial information to move the actuator inwards while
servoing on the edge of the tracks. The trigger
20 patterns are used to derive precise timing or circumferential information for use in writing product servo-patterns. Using the radial and trigger patterns, the product servo-patterns are written. Particularly, the radial and trigger patterns are
25 used to precisely line up the product servo-patterns track to track.

In one example, in order to write a track of servo-patterns, the radial propagation controller instructs the pattern generator to write a sequence
30 of radial bursts on a track of the storage media via

-17-

read/write interface card 324. The read/write interface card provides a signal to the transducer to write patterns on the storage media. Further, the timing propagation controller controls the pattern generator to write product servo-patterns at specified locations.

Although the pattern generator is depicted as a separate component within the self-servowrite apparatus, it can be a part of other components, such as, for instance, the radial propagation controller and/or the timing propagation controller.

The output of pattern generator 320 (e.g., a stored pattern) is, for example, input to read/write interface card 324, which generates one or more signals representative of the stored pattern. The signals are input to recording head 304, which writes the signals on storage media 306.

In addition to the above, in one example, self-servowrite apparatus 300 includes motor controller 322 used to rotate storage media 306 and to derive an index pulse 323 from motor 312 of the storage device.

Described above is one example of a self-servowrite apparatus coupled to a storage device. The self-servowrite apparatus and/or the storage device may include additional, less and/or different components than that described above without departing from the spirit of the present invention. For instance, one processor may be used to perform the operations of PC controller 314, processor 334 and/or processor 344. Alternatively, a plurality of

-18-

processors may be employed to perform the functions of one or more of the above-described processors. For example, processor 344 may include one or more processors (referred to as a processing unit).

5 Further, one or more timing propagation controllers may be used to perform the functions provided by timing propagation controller 318. These one or more controllers form a controlling unit. Similarly, one or more radial propagation controllers
10 may be used to perform the functions provided by radial propagation controller 316. Again, the one or more controllers form a controlling unit. It is also possible that the functions of the radial and timing propagation controllers can be combined into one or
15 more controllers, which also can be referred to as a controlling unit.

Typically, a commonly used, servo architecture known as "embedded servo" in which servo pattern information is present on all disk surfaces is used
20 in disk drives. A dual revolution clock propagation process described herein and in U.S. Patent No. 5,485,322 is used to gate pattern generator 320 to write servo patterns onto all surfaces. The ability to accomplish this with a minimum of revolutions is
25 important in the case when the servowriter is external to the disk drive which is contemplated to be the preferred commercial implementation of this invention. To write the embedded servo requires a clock to position the embedded servo
30 circumferentially.

-19-

Any process used to generate a clock for the pattern generator by self-propagation using only the disk drive data heads typically requires several thousand steps during the servowriting of the disk surface. Since a single head cannot write and read simultaneously, self-propagation requires dividing a track on the disk into alternating sectors, such that timing synchronization is obtained in one sector just prior to writing the next sector as shown in FIGs. 2a-2b. After moving the head to an initial starting track, track #0, STEP 200, trigger patterns (TP) are written on the odd numbered sectors, STEP 202. The head is displaced a fraction of a track to servo track #1, STEP 204, and the odd numbered sectors 1, 3, 5, ... 59 are used for synchronization in writing the subsequent TP's on the even numbered sectors 0, 2, 4, ... 60, STEP 206. The head is again displaced a fraction of the track to servo track #2, STEP 208, and the roles are reversed, with the even numbered sectors used for synchronization in writing the subsequent odd numbered sectors, STEP 210. This process continues until the head is displaced across the recording surface.

Each time a sector is written, a small but unavoidable timing error called the base error occurs due to both disk rotational velocity changes and electrical noise in the readback signal used for synchronization. These errors are replicated on the next step as the written sectors change over to synchronization sectors. A new and independent set of random errors is added here as well. Thus, the self-propagation process involves a replication and summation of the random errors in each step. Left

-20-

uncorrected, statistically such errors grow as the root mean square of the number of steps. Since the process of synchronization and writing is causal, i.e. synchronization occurs before writing on each step, the sequence of random errors that determines the location of a given sector timing pattern can be traced back in a spiral path which is shown by the arrows labeled Path1, Path2 and Path3 of FIG. 2b. The paths run in parallel and for adjacent radial locations at each sector are totally independent so the track to track misalignment ends up as the difference between two independent random walks, giving an additional factor of the square root of 2. Therefore, after 10,000 steps, the RMS track to track error would be 141 times the base error. It should be noted that this process can work with other than alternating patterns limited to two. For instance, two or three patterns may be used for clock propagation.

As described in U.S. Patent No. 5,485,322, errors in the pattern propagation process can be detected and corrected to produce precise magnetic pattern alignment from track to track. Errors written at each step are measured during a subsequent revolution of the disk and are accounted for and corrected. For example, in FIG. 2b prior to writing TP 26, the interval between TP 24 and TP 42 is measured on an extra revolution of the disk and stored as a time interval T45. The time interval T45 is used when the head is positioned on servo track #3 and triggers on TP 24 to write TP 26 aligned to TP 42. The extra revolution of the disk breaks the causal chains denoted by Path 2 and Path 3,

-21-

effectively locking together the normally independent random walk paths and preventing the growth of track to track misalignment. This process, as described in United States Patent No. 5,485,322, is referred to
5 herein as the "dual revolution clock propagation process."

In FIGs. 4a-4b, there is shown one embodiment of a process by which trigger patterns are used to write servo patterns on a first surface using a first
10 recording head and other surfaces by switching to other recording heads on other recording surfaces. The recording head is set to read mode and triggers on TP#0, which begins gating pattern generator 320 to write servo pattern SP#0, then the next recording
15 head in the stack of a multiplatter disk drive is selected and a second servo pattern SP#1 is written on surface #1 and repeated to N surfaces. The number N is limited by the time required to write each surface and switch the heads. At the end of the Nth
20 surface, the head is switched to the first surface #0 in time to read the next sector TP#1. This process makes clear the advantage of trigger patterns as their short time allows other surfaces to be written with servo patterns within the same revolution of the
25 disk, thus reducing servo write time. In particular, servo-patterns can be written while writing trigger patterns.

GEOMETRICAL EFFECTS RESULTING IN SYSTEMATIC ERRORS

It is desirable for clock propagation processes
30 to have systematic errors reduced during the propagation process. Such errors contribute to track

-22-

misalignment and/or rotation of the pattern with respect to a fixed frame. The most obvious systematic error, as described in IBM Technical Disclosure-Bulletin, Vol. 33, No. 5 (October 1990), is the electronic delay in the read to write circuitry. However, the prior art does not teach that radial varying systematic errors (which change with radial position) due to geometric effects which are particular to a head and actuator design are present. If these errors are not compensated, they can reduce the track to track accuracy of the propagation process and can accumulate to result in rotation of the pattern with respect to an index (fixed reference). This rotation is shown graphically in FIG. 8, where each TP 800 on a subsequent servo track is displaced from the previous servo track due to a systematic error causing both pattern rotation and a fixed track to track misalignment error.

In the case where the pattern rotation matches the trajectory of the actuator during a seek, no shift in timing relative to the index related to the rotational orientation of the disk relative to the base plate (which does not change with radial position) will be present. This is the desired pattern rotation since it simplifies the disk file servo during long seeks. Thus, patterns which are written in such a manner as to have no timing shift relative to an index related to the rotational orientation of the disk will necessarily be of the desired type. Several examples of systematic errors are described below, but it should be understood that other similar effects can result from particular head and disk drive design. In general, for a given

-23-

systematic error, there are three techniques which can be used to remove the systematic error:

- 5 1) Measurement of the error at one or more known radii which are used to compute the correction term at each propagation step;
- 2) In-process correction of the error by internal measurements during the propagation process; and
- 10 3) Measurements of the error in the disk file, by external means, which are used to correct all disk drives of similar design.

RADIAL DEPENDENT TIME DELAY FOR
INDEPENDENT READ/WRITE SENSORS

15 The dual revolution timing pattern process described in U.S. Patent No. 5,485,322 is modified when the recording transducer has write and read elements which are separate as shown in FIG. 5a. In this case, a time delay or advance (relative to the case where the write and read elements are not
20 separate) is required to write a second trigger pattern a specified physical distance after a readback trigger pattern. This time delay is a function of the disk linear velocity given by:

25

$$\frac{W}{V}$$

where W is the separation between read element 46 and write element 48, and V is the disk linear velocity.

-24-

Further, in the case where the head is skewed relative to the track, as for example, would occur on a rotary actuator, the "apparent" separation W of the read and write transducers, as projected along the recorded track, is modified by the cosine of the skew angle of the recording head and will also vary as a function of radius (see FIG. 5b). The time delay due to the separation effect is given by:

$$\text{DELAY}_{\text{Separation}} = \frac{W}{\cos(\theta) \Omega R}$$

where θ is the skew angle of the recording head, Ω is the disk rotation speed, and R is the radius of the track.

The read to write separation W can be measured, for example, using the product data head by writing a TP 50 (FIG. 5c), triggering on that trigger pattern on a subsequent revolution and writing a second trigger pattern TP 52, a time T_{54} later. Subsequent measurement of the actual time between the two trigger patterns is equal to the time T_{54} plus any delay in the electronics (which is fixed) and the delay due to the physical read to write separation W . Repeating this measurement at two known radii (R_1 and R_2), possibly the innermost accessible data track or inner radius (ID) and the outermost accessible data track or outer radius (OD), with a known skew angle can be used to compute the separation between the read and write elements. The measured total delay is given by:

-25-

$$RW_{\text{Delay1}} = \frac{W}{\cos(\theta_1) \Omega R_1} + \text{Delay}_{\text{electronic}}$$

$$RW_{\text{Delay2}} = \frac{W}{\cos(\theta_2) \Omega R_2} + \text{Delay}_{\text{electronic}}$$

5 where this total delay referred to as the read to write delay, includes a delay due to the read to write separation and an additional delay due to the electronics path in either or both the read and write chain of the recording head.

10 The above relationships can be solved for W as given by:

15

$$W = \Omega X \left[\frac{RW_{\text{Delay1}} - RW_{\text{Delay2}}}{\frac{1}{\cos(\theta_1) R_1} - \frac{1}{\cos(\theta_2) R_2}} \right]$$

The delay for each propagation step can then be computed and updated as the timing pattern is propagated across the disk surface (i.e., technique #1 of systematic error removal).

20

Alternatively, as noted in technique #2, the read to write delay can be measured during the propagation process and used to correct for the variable delay. For the case of the dual revolution timing pattern process, a measurement of the delay

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-26-

and correction values (e.g., HFM, HFS, HFC and SD where gp, gd and gi (each of which is explained later below) are set to 0) is available on each readback measurement revolution, which is described in the
5 section "Process with Systematic Error Removal" below.

In some cases, it may be desirable to use measured delays to find the absolute radial position of the head. For a given disk file, the relationship
10 between radial position of the head and the skew angle may be ascertained. Once the separation between the read and write elements is known, the electronic component of the delay may be determined by solving the above equation for the read to write
15 delay at a given known radius. The same equation may now be solved to determine absolute radial position by using the read to write delay measured with the head at any other location.

READ TO WRITE NON-PARALLELISM

20 An additional systematic error occurs if the read element of a recording head is non-parallel to the writing element. This is shown in FIG. 6a where the written trigger patterns, TP 64, TP 66, and TP 68 are non-parallel to read element 62. TP 68 is
25 written approximately one half off-track from TP 64 and TP 66. When read element 62 on track center 70 reads the trigger patterns, the time interval measured between TP 64 and TP 66 is given by D1. The time interval measured between TP 66 and TP 68 is
30 equal to D2. The time interval D2 will be longer than D1 due to the fact that TP 68 is off track and its

-27-

angle results in a shift in the apparent center of the trigger pattern. To further clarify this effect, when the read and write elements are parallel as shown by trigger patterns TP 72, TP 74 and TP 76

5 (FIG. 6b) the measured intervals per the above description result in the two measured intervals D1 and D2, which are equal. It should be noted that any non-parallelism between the read element and the written transition will cause this effect and it need
10 not be limited to a constant angle between the read and write elements. Specifically, a bending or warping of the written transitions arising from edge effects in the write process will produce this effect.

15 This error can be removed during the propagation process by measuring the systematic error of intervals comprised of both on-track trigger patterns versus those intervals with one on-track and one off-track signal and storing the value.

20 Alternatively, as noted in technique #2, this error can be measured during the propagation process, as a separate periodic measurement step. In particular in the case where the read and write elements have a more complex geometric misalignment
25 rather than simply non-parallel, then the delay may depend non-linearly on radial location. Correction of the effect would require periodic measurement during the propagation process.

30 This geometric effect can create a pattern spiral which is shown in FIG. 7A. Trigger patterns TP 82, TP 84 and TP 86 are aligned to minimize the

-28-

track to track misalignment of the pattern, but the result is a rotation of the pattern from Index 80 in the time domain. Pattern rotation can be reduced by using a once per revolution index (i.e., an index
5 fixed to an absolute frame, e.g., a motor index), as described in the "Process With Systematic Error Removal" below.

MISALIGNED HEAD MOUNTING

10 An additional geometric effect can occur if the recording head is non-parallel to the direction of actuator motion. When the trigger patterns are aligned to minimize the track to track error, a pattern rotation will result. A simple example is shown in FIG. 7B, in which a head is non-parallel to
15 the motion of a linear actuator. When the trigger patterns TP 90, TP 92, and TP 94 are aligned, a pattern rotation occurs. Removing the pattern rotation shown by TP 90, TP 96 and TP 98 results in a track to track misalignment. A similar effect
20 occurs when a head is misaligned on a rotary actuator.

PROCESS WITH SYSTEMATIC ERROR REMOVAL

In the propagation process shown in FIG. 2a, the odd numbered sectors are used for synchronization in
25 writing the subsequent even numbered sectors and on the next step (after moving the head a short distance radially), the roles are reversed, with the even numbered sectors used for synchronization in writing the subsequent odd numbered sectors. Although the
30 growth of random errors is removed by the measurement

-29-

feedback process, a systematic error can result in a fixed track to track error and in a rotation of the entire servo pattern with respect to a fixed reference frame. This is shown in FIG. 8 where
5 subsequent written trigger patterns are displaced a fixed distance from the previous servo track due to a systematic error.

One embodiment of a flow chart in which systematic errors are reduced and the growth of
10 random errors are controlled is shown in FIG. 9 and described below.

STEP 100) The process is initiated by writing a sequence of trigger patterns and measuring the delay between read and write, as
15 previously described, and storing the delay as a variable D_{RW0} . The TP shift due to read/write parallelism is checked and measured and stored as D_{S0} .
20

STEP 102) The read to write delay determined from STEP 100 is used to write, for instance, the even numbered TPs on the disk on, for
25 instance, servo track number 0. The location of the first TP with respect to the index is recorded and the index correction is set to zero.

-30-

STEP 103) The head is moved a fraction
(e.g., $1/3$) of the track width.

5 STEP 104) The alternate numbered TPs are
written. This is initially, for
instance, the odd TPs, but will
alternate between even and odd on
successive propagation steps.

10 STEPS 105) Every interval corresponding to
the time between trigger patterns
is measured.

15 At STEP 105A, the intervals are divided into
two groups, Interval Full to Half
(I_{FH}) and Interval Half to Full
(I_{HF}). The I_{FH} corresponds to a
time interval beginning with a
full on-track TP and ending with
an off-track TP. The I_{HF}
20 corresponds to a time interval
beginning with an off-track TP
and ending with an on-track TP.
Combined these account for all
the intervals on the disk. Each
interval is measured using, for
instance, a time interval
25 analyzer.

At STEP 105B, the location of the first TP in
the group written with respect to
the rotational index is recorded
using, for example, a time

-31-

interval analyzer, during the same revolution of the disk.

STEPS 106) The measured intervals are used to calculate the time delay corrections.

5

At STEP 106A, the I_{HF} are used to determine the read to write delay to be used in the next TP write.

At STEP 106B, the I_{FH} are input to the clock algorithm and corrections are computed to eliminate the random growth of errors in the next TP write. Elimination of the random growth of errors is described in detail in commonly assigned U.S. Patent No. 5,485,322, issued January 16, 1996, entitled "Method And System For Writing A Clock Track On A Storage Medium," which is hereby incorporated herein by reference in its entirety.

10

15

20

At STEP 106C, the location of the first TP to the index is used to compute a new index correction to prevent the rotation of the pattern with respect to index. It should be noted this feature may be disabled for example to minimize track to track error by allowing

25

30

-32-

the pattern to rotate as in FIGs. 7a-7b. The index can be obtained from the current waveform in the DC brushless motor typically used in disk drives or from any other available once-per-revolution signal derived from the orientation of the disk relative to the base plate of the drive. In one example, the index correction is equal to a predetermined desired time interval (e.g., 50 microseconds) minus the recorded time interval (between the index and the first TP).

STEP 107)

The outputs of each of the above described processes in STEPS 106A, 106B and 106C are used to compute the desired delay to write the alternate trigger patterns at the next radial location. This is described in further detail below.

STEP 108)

The servo-track count is checked to determine the end of the process (e.g., 18,000 servo-tracks).

If the process has not ended, the process loops back to STEP 103.

-33-

In the above process, in practice, one may average the measurements of the systematic errors on two or more subsequent servo-tracks prior to making corrections to the computed delay values for each interval.

Another example of reducing systematic and random errors in a pattern propagation process is described in detail below with reference to FIGs. 10-18. In one embodiment, the logic within those figures is performed by one or more controllers (e.g., a controlling unit), such as timing propagation controller 318 (FIG. 3a). For example, many of the calculations and comparisons are performed by one or more processors (e.g., a processing unit) of the controller. Further, the time measurements are performed by, for example, either the time interval analyzer or the motor index in combination with the counter within the processor, as described herein. Additionally, the programmable delay is used, as one example, to shift location of patterns.

In another embodiment, many of the calculations and comparisons are performed by one or more computing units, which may or may not be a part of controller 318 or any controlling unit. In one instance, a computing unit is a processor. In further embodiments, other components may be used to perform the below-described functions and these components may or may not be a part of controller 318 or any controlling unit. For instance, a measuring unit can be used to measure time intervals, and the measuring unit may or may not be a part of controller

-34-

318 or any controlling unit. As a further example, a processing unit (e.g., one or more processors) that is not considered a part of the controller or controlling unit may be used to perform at least a portion of the logic within controller 318.

Referring to FIG. 10, initially a start-up procedure is implemented, which is used to initialize various variables to be used during the systematic and random error elimination process, STEP 1000. One example of a start-up procedure is described in detail with reference to FIG. 11. An initial value of the read/write delay (systematic delay (SD0)) is measured in a manner described above with reference to FIG. 5c, STEP 1100. Additionally, a value for a target index time (IT), which represents the target interval between the index (e.g., the motor) and the first trigger pattern, is either measured or chosen, STEP 1102. In one embodiment, IT is set to 50 microseconds.

Further, a value for a valid interval window (VI) is set equal to a valid interval window nominal value (VI_{nominal}), such as, for instance, 35 nanoseconds, STEP 1104. The valid interval window is used as an error check; in particular, it defines how far away from the anticipated trigger location an actual measured trigger pattern can be to conclude that it is valid. Also, an estimate of a current index location (IS) is set to the target index time, which is updated as the technique proceeds along to the target, STEP 1106.

-35-

In addition to the above, a number of other variables are initialized, STEP 1108. In particular, a step value (N) is set equal to zero. In one example, there are 18,000 steps. Further, an index correction value is set equal to zero, as well as a half to full estimate (HFS) and a half to full correction (HFC). Additionally, a local average interval error (LAIE) is set to zero, as well as an integral algorithm correction (IAC) for all i. A trigger point valid flag is set to false for all of i and a value representing the number of equally spaced trigger patterns (Nint) is set equal to 90, as one example. As used herein, all index i are assumed to be modulo and can range from zero to Nint-1 (i.e., eighty-nine).

After the above values are initialized, an initial set of equally spaced trigger patterns (Nint) are written at intervals TI_i with the first trigger pattern near the target index time with respect to the index, STEP 1110. All TI_i are equal to the target average interval (TAI) to start with, which is the nominal revolution time divided by the number of intervals in a revolution.

Subsequently, a measured interval (MI_0) is measured at trigger pattern zero using, for instance, a time interval analyzer, STEP 1112, and a variable referred to as TS (time slip) is set to zero, STEP 1114. This value represents an error handling variable that keeps track of the magnitude of the error in an erroneous trigger. This logic assumes the existence of hardware, which generates a fake trigger pattern if a valid or erroneous trigger

-36-

pattern is not received within a specified time;
 i.e., trigger patterns valid, erroneous or fake are
 generated near every anticipated trigger pattern
 location. In the beginning, it is assumed there are
 5 no errors and therefore, TS is set to zero.
 Thereafter, an interval (MI) is measured at trigger
 pattern 1, STEP 1116, as described in detail below.

One embodiment of measuring intervals at trigger
 pattern one ($TP_{(1)}$) is described in detail with
 10 reference to FIG. 12. Initially, the interval at TP_i
 where i is equal to 1 is measured using, for example,
 the time interval analyzer, STEP 1200. (That is, the
 interval between $TP_{(0)}$ and $TP_{(1)}$ is measured.)
 Thereafter, the measured interval is corrected for
 15 previous invalid trigger patterns, STEP 1202. This
 is accomplished by setting MI_i equal to $MI_i + TS$
 (i.e., $MI_i = MI_{(0)} + TS$). Since the first trigger
 pattern is assumed to be valid, TS is set to zero and
 no correction is made.

20 Next, a determination is made as to whether the
 immediately corrected value of MI_i minus the value of
 the target interval ($TI_{(0)}$) is greater than the valid
 interval window (VI), INQUIRY 1204. If $|MI_i - TI_i|$ is
 greater than the valid interval window, then $MI_{(0)}$ is
 25 considered to be invalid. Thus, the value of time
 slip (TS) is set equal to $MI_i - TI_i$, and the trigger
 pattern valid flag ($TPV_{(0)}$) is set to FALSE, STEP 1206.
 Thereafter, another inquiry is made as to whether the
 valid interval window is greater than a maximum value
 30 that has been set (VI_{limit}), INQUIRY 1208. If the valid
 interval window is greater than the maximum (e.g.,
 700 nanoseconds), then the process for measuring the

-37-

interval at the first trigger pattern is complete, STEP 1218. However, if the valid interval window is less than or equal to the maximum, then the valid interval window is increased by a valid interval increment (VI_{inc}), STEP 1210 and the measurement of MI_i is complete. One example of a value for the valid interval increment is 35 nanoseconds.

Returning to INQUIRY 1204, if the measured interval is valid, then the time slip is set equal to zero, the trigger pattern valid flag is set equal to TRUE and the valid interval window is set equal to the nominal value ($VI_{nominal}$), such as, for instance, 35 nanoseconds, STEP 1212.

Subsequently, the trigger pattern valid flag for interval $i-2$ is checked to see if the trigger pattern at that location was valid, INQUIRY 1214. If it was not valid, then again the measured interval process is complete and the local average interval error (LAIE) is left unchanged, STEP 1218. However, if the trigger pattern at that location is valid, then the local average interval error (LAIE) (i.e., the velocity error) is updated, STEP 1216.

In one example, the local average interval error is computed as follows:

$$LAIE = LAIE + q \times \left\{ \left([MI_{(i)} + MI_{(i-1)} - TI_{(i)} - TI_{(i-1)}] \div 2 \right) - LAIE \right\},$$

-38-

where q represents a value, which determines how fast the LAIE is going to track the difference between actual interval measurements and expected nominal velocity interval measurements, and is equal to a
5 fraction such as .1.

Subsequent to updating the local average interval error, the process for measuring the interval at trigger pattern one is complete, as well as the start up procedure of FIG. 10. Therefore,
10 processing proceeds with a read procedure, STEP 1002 (FIG. 10). One embodiment of the read procedure is depicted in FIG. 13 and described in detail herein.

Initially, index i is set equal to 2, since the read is going to read back the interval starting with
15 $i = 2$ and go around past zero to one, STEP 1300. Thereafter, the interval at trigger pattern two is measured, STEP 1302, in the manner described above for measuring the interval at trigger pattern one (see FIG. 12). Subsequent to measuring the interval,
20 the index is incremented by one, STEP 1304, and an inquiry is made to determine whether the process is complete, i.e., whether i has reached 2, again, INQUIRY 1306. If i is not equal to 2, then a further determination is made as to whether i is equal to a
25 value of N_{int} , INQUIRY 1308. If i is not equal to N_{int} , then processing continues at STEP 1302 "Measure Interval At TP_i ." If however, i is equal to N_{int} , then i is recalculated by subtracting N_{int} from i , (i.e., $i = i - N_{int}$), STEP 1310. Thereafter,
30 processing continues with STEP 1202 "Measure Interval At TP_i ."

-39-

In addition to the above, sometime after STEP 1310, an index estimate (IS) is measured and updated. One embodiment for measuring and updating the index estimate is described in detail with reference to

5 FIG. 14. Initially, the time interval between the index and the first available non-fake (i.e., valid or erroneous) trigger pattern after the index, which is usually either at TP_0 or TP_1 , is measured using, for example, a time interval analyzer, STEP 1400.

10 Further, a trigger pattern indice (TPind) is set equal to zero, STEP 1402. Subsequently, a determination is made as to whether the measurement (IM) of the interval between the index and the first available non-fake trigger pattern is greater than a

15 target (IT) plus a variable IW (i.e., $IM > IT + IW?$), which reflects the allowed error from the target for the measurement to be considered valid, INQUIRY 1404. If IM is greater than this value, then the trigger pattern indice is incremented by one and IM is

20 decremented by $TI_{(TPIND)}$, STEP 1406. Thereafter, processing returns to INQUIRY 1404, " $IM > IT + IW?$ ".

When IM is less than or equal to $IT + IW$, a check is made against the other end of the window. In particular, a determination is made as to whether

25 IM is less than $IT - IW$, INQUIRY 1408. If IM is less than $IT - IW$, then the measurement is invalid and processing of the measurement and update of the index estimate (IS) is complete, STEP 1410.

However, if IM is not less than $IT - IW$, then

30 the measurement may or may not be good. Thus, a determination is made as to whether the trigger pattern valid flag (TPV_{TPIND}) is equal to true. If it

-40-

is not equal to true, then the measurement is invalid and processing is complete, STEP 1410. However, if the flag is set equal to true, then it is a good measurement and an index estimate (IS) is updated as follows:

$$IS = IS + f \times (IM - IS),$$

where f is a variable approximately equal to 0.1, which determines how fast IS is going to track IM. (In another embodiment, the above windowing of STEPS 10 1402 and 1412 are not used to determine if the measured time interval is valid. Other procedures may be used. The index estimate is updated when the measured time interval is valid.)

After measuring and updating the index estimate, 15 processing continues with FIG. 13. Specifically, after the index estimate is measured and updated and/or after a positive result is received from INQUIRY 1306, the measured intervals ($MI_{(i)}$) are corrected, STEP 1314.

20 One embodiment for correcting the measured intervals is described in detail with reference to FIG. 15. In one example, the operations described within FIG. 15 are performed by one or more processors (e.g., a processing unit) of timing 25 propagation controller 318. In another embodiment, the processing unit need not be a part of the propagation controller.

Referring to FIG. 15, initially, an index correction is computed, STEP 1500, as follows:

-41-

$$IC_n = gp \times (IE_n) + gi \times \sum_0^n IE_n + gd [IE_n - IE_{n-Q}]$$

where:

- 5 IC is equal to the index correction, which is
 indicative, e.g., of the location of a
 trigger pattern on the disk relative to the
 rotational index of the disk;
- 10 gp is equal to a proportional gain which is
 approximately 0.4, in one embodiment;
- gi is equal to an integral gain which is
 approximately equal to, for instance, 6×10^5 ;
- 15 gd is equal to a differential gain, which is
 approximately equal to, for instance, 0.01;
- Q is a variable which reflects how many steps
 occur between the measurements, which are
 going to be used to determine the slope,
 and is equal to, for instance, 10; and

20 $IE_n = IS - IT.$

After computing the index correction, the index variable i is initialized to zero, STEP 1502. Thereafter, a determination is made as to whether the trigger pattern valid flag at index i (TPV_i) and the
25 trigger pattern valid flag at $i - 1$ ($TPV_{(i-1)}$) are equal

-42-

to TRUE, INQUIRY 1504. If both of these flags are true and the measured interval is full to half, then the index correction measured interval (ICMI) of i is computed, as follows:

$$5 \quad \text{ICMI}_i = \text{MI}_i - \text{IC}_N.$$

However, if both of the flags are true and the measurement is half to full, then the index correction measured interval is equal to the following:

$$10 \quad \text{ICMI}_i = \text{MI}_i + \text{IC}_N.$$

Subsequently, or if at least one of the trigger pattern valid flags is false, then a determination is made as to whether i is less than $N_{\text{int}} - 1$, INQUIRY 1508. When i is less than this value, then i is incremented by 1, STEP 1509, and processing continues for the next index with INQUIRY 1504. However, when i is greater than or equal to $N_{\text{int}-1}$, then an average interval is computed using the following equation, STEP 1510:

$$20 \quad \text{AI} = \sum_{0}^{N_{\text{int}}-1} \text{ICMI}_i \div N_{\text{int}}.$$

Thereafter, i is set equal to zero again and another determination is made as to whether the trigger pattern valid flags at index i and at index $i-1$ are equal to true, INQUIRY 1514. When they are equal to true, then a corrected measured interval is computed as follows, STEP 1516:

-43-

$$CMI_i = ICMI_i - (AI - TAI).$$

After computing CMI or when at least one of the trigger pattern valid flags is invalid, a further determination is made as to whether i is less than N_{int-1} . When i is less than this value, i is incremented by 1, STEP 1520, and processing continues for the next index at INQUIRY 1514. However, when i is greater than or equal to N_{int-1} , then the corrected measured interval processing is complete, STEP 1522.

Returning to FIG. 13 and in particular STEP 1314, subsequent to correcting the measured intervals, two paths are taken, each of which is described below. One of the paths includes, for instance, computing a half/full measurement, as follows:

$$HFM = \left[\sum_{all(i)} CMIhf_{(i)} - \sum_{all(i)} CMIfh_{(i)} \right] / N_{int},$$

wherein CMIhf is the subset of the CMIs, which are measured from half to full; and CMIfh is the subset of the CMIs, which are measured from full to half.

Subsequent to calculating HFM, a half to full error (HFS) is updated by using the following formula, STEP 1318:

$$HFS_N = HFS_{N-1} + \alpha \times [HFM - HFS_{N-1}]$$

where α is equal to, for instance, .025.

-44-

Thereafter, a delay correction is computed as follows, STEP 1320:

$$HFC = bp(HFS_{(N)}) + bi \sum^{all} HFS_{(N)} + bd(HFS_{(N)} - HFS_{(N-w)}),$$

5 where w is equal to, for instance, 10.

Subsequently, a new systematic delay (SD) is computed by adding the delay correction to the initial value of the systematic delay (i.e., $SD = SD0 + HFC$), STEP 1322. The new systematic delay adjusts
 10 where the trigger patterns on the next step are to be written. This ends the first path.

The second path taken after correcting the measured intervals includes computing an algorithm correction (i.e., random error correction) and target
 15 intervals, which are described in detail with reference to FIG. 16.

In one embodiment, initially an algorithm correction (AC_i) is computed, STEP 1600. In one example, $AC_i = (TAI - CMI_i) \times \text{a fraction, such as .3.}$
 20 (Algorithm correction is also described in commonly assigned U.S. Patent No. 5,485,322, issued on January 16, 1996, entitled "Method And System For Writing A Clock Track On A Storage Medium," which is hereby incorporated herein by reference in its entirety.)

25 Thereafter, an integral algorithm correction used in correcting circumferential systematic errors is computed using the following formula, STEP 1602:

-45-

$$IAC_i = IAC_i + AC_i.$$

Additionally, target intervals are computed, as follows, STEP 1604:

$$TI_i = CMI_i + s_i \times AC_i + t_i \times IAC_i,$$

5 where:

s_i are typically equal to 1; and

t_i are typically equal to 0.

10 Once these computations are made, processing of the compute algorithm corrections and target intervals, as well as processing of the read procedure is complete (see FIG. 13) and processing continues with STEP 1004 of FIG. 10.

15 In particular, a step procedure is performed in order to move to the next servo-track. One embodiment of the step procedure is described with reference to FIG. 17. Initially, a command to move the actuator to the next servo-track is sent to the system that moves the actuator (e.g., a radial propagation controller or a pusher), STEP 1702.

20 Then, an index value, i , is set equal to 2, STEP 1704. Thereafter, a measurement is taken at trigger pattern i , STEP 1706. In particular, the interval at TP_i is measured as described above with reference to FIG. 12.

-46-

Subsequent to measuring the interval, a determination is made as to whether i is less than $N_{int}-1$, INQUIRY 1708. If i is greater than or equal to $N_{int}-1$, then processing of the step procedure is complete, STEP 1710. However, if i is less than $N_{int}-1$, then i is incremented by 1, STEP 1712, and processing continues with measure interval at TP_i , STEP 1706.

Returning back to FIG. 10, in addition to the step procedure, a procedure to write trigger patterns on the next track (or the next radial position) is performed, STEP 1006. One embodiment of the write procedure is described in detail with reference to FIG. 18.

Initially, i is set equal to zero, STEP 1800, and then, the interval at TP_i is measured, as described above, STEP 1802. Thereafter, a determination is made as to whether the index value is equal to odd or even. This will depend on whether the write revolution is triggering on odds and writing on evens, or vice versa. If the revolution is triggering on odds and i is equal to odd (or if the revolution is triggering on evens and i is equal to even), then a new trigger pattern is written with a delay of $TI_{i+1} - SD - TS + m \times LAIE$, where m is equal to approximately 1.0, in one example.

Next, a corrected measured interval for $i+1$ is updated as follows, STEP 1808:

$$CMI_{i+1} = TI_{i+1} - (t_{i+1} \times IAC_{i+1}).$$

-47-

Sub B1
 Additionally, CMI_{i+2} is updated as follows, STEP 1810:

$$CMI_{i+2} = CMI_{i-2} - (S_{i+1} \times AC_{i+1}).$$

5 Thereafter, or if i is not equal to odd (or to even), then a determination is made as to whether i is equal to $Nint-1$, INQUIRY 1812. If i is not equal to $Nint-1$, then i is incremented by one at STEP 1814 and processing continues with STEP 1802 "MEASURE INTERVAL AT TP_i ." However, if i is equal to $Nint-1$,
 10 then the interval is measured at TP_0 and TP_1 , STEPS 1816 and 1818.

15 In addition to the above, sometime between STEPS 1800 and 1816, the index estimate is measured and updated, as described with reference to FIG. 14, STEP 1820. Thereafter, processing continues with STEP 1816. Further, sometime after STEP 1816 and before STEP 1310 of FIG. 13, the index estimate is measured and updated again.

20 Returning to FIG. 10, after the write processing is complete, then the step number is incremented by 1, STEP 1008, and a determination is made as to whether the processing is complete, INQUIRY 1010. If the processing is not complete, then flow returns to STEP 1002 "READ."

25 VELOCITY ERROR CORRECTION

Variations in the disk rotation speed will cause errors in the propagation process described above. In U.S. Patent No. 5,485,322, it was taught that the

-48-

magnitude of this error is proportional to the interval spacing. Therefore, this error can be minimized by reducing the interval size, which corresponds to the time between any two consecutive odd (or any two consecutive even) trigger patterns until this term is negligible. In certain cases, the reduction of the interval to reduce this error to a negligible level may not be practical.

In accordance with the principles of the present invention, in those cases where intervals cannot be reduced, the velocity of the disk is measured "on the fly." Errors in the written TP location will occur when the velocity of the disk is different during the read and the write step as in the dual revolution timing pattern propagation of U.S. Patent No. 5,485,322. In one embodiment of the present invention, the nominal interval length corresponding to the average of the interval times (either or both readback and write interval times) for one complete rotation is used to estimate the disk average or nominal velocity.

In FIG. 19, by measuring the time interval between the TPs during the write process, a computation of the local disk velocity (i.e., substantially instantaneous velocity) can be obtained by comparing this interval (i.e., T116) with the nominal or expected interval at the nominal velocity. For example, computed velocity = nominal velocity x $(T116 \div (2 \times \text{nominal interval time}))$.

As the rate of change of velocity is limited by the disk inertia, a set of interval measurements

-49-

immediately preceding the TP to be written may be averaged to estimate the current disk velocity. For example, when the head is centered on servo track #1, intervals T 114 and T 116 can be measured to estimate the local disk velocity (i.e., LAIE + Nominal Interval = TAI) prior to writing TP 118.

Another implementation of velocity error correction is described above with reference to FIGs. 12 and 18.

10 WINDOWING

As described above, windowing is used, in accordance with the principles of the present invention, to determine whether a particular trigger pattern is within a valid trigger pattern region (see, for example, FIG. 12).

In a further aspect of the present invention, a hardware window is created to detect a trigger pattern, thereby eliminating false triggers in regions outside the expected region.

For example, with reference to FIG. 23, trigger pattern detector 340 (FIG. 3C) includes, for instance, a comparator, which is used to detect a trigger pattern written on the disk. In one embodiment, the detector is enabled by lowering the comparator level (e.g., via trigger pattern window 346) at a time T_w (a time before the trigger pattern is expected), so that a read-back signal of the trigger pattern is higher than the comparator level. When the read-back signal is higher, then the

-50-

detector is triggered. The comparator level is then further adjusted to zero. In particular, as the read-back signal comes down through zero, the comparator will go low, and the trigger pattern is
5 detected on the negative edge of the comparator output.

When an expected trigger does not occur within a given time period, an automatic false (e.g., fake) trigger is created by an electronic signal generated
10 by the hardware.

TECHNIQUE FOR IMPROVED INTERVAL CONTROL

The previously disclosed technique of U.S. Patent No. 5,485,322 employs interval measurements during the trigger pattern propagation. When an
15 error occurs in an interval, it is unknown which of the two TPs defining the interval is erroneously positioned. As a result, when the technique propagates with correction values of F (F is defined below) less than 1, the TP location errors propagate
20 (in a decaying fashion) to neighboring locations. A demonstration of this is diagrammed in FIG. 20a. On servo track #1 (ST#1), TP 132 is erroneously shifted with respect to TP 150 resulting in an interval measurement T145 less than the nominal. On the next
25 step of the process, the head is positioned on servo track #2 and TP 134 is written with an error to correct for the short interval T145. Subsequent writing of servo tracks #3 and #4 shows that the error of T145 propagates in a decaying fashion.

-51-

In accordance with the principles of the present invention, in the technique for improved interval control, information about the position of a particular TP is extracted. Rather than specifying a particular interval from the previous TP as the
 5 desired nominal position, the interval data from surrounding TPs are used to provide position information. The interval between the TPs currently being evaluated and each TP within a specified number
 10 of transitions is computed.

As an example of using the nearest neighbor comparison, the location of TP 132 is evaluated by measuring the interval T124 and T146 (see FIG. 20b). Similarly, TP 150 is evaluated by measuring T135 and
 15 T157. In the case where T124 and T146 are not equal, and T135 and T157 are equal, then the location of TP 132 is in error and not that of TP 150. In actual practice, this process is extended beyond nearest neighbors and averaged for an appropriate specified
 20 number of neighboring intervals to provide information on TP placement.

One embodiment of implementing the nearest neighbor comparison is depicted in the below pseudocode.

```

25  for (i=1;i<=SECTORS;i++)
      {
          t=i+SECTORS
          if (m != !m)
              {
30              rangetotal=0;
                  for (u=-(RANGE-1),u<=(RANGE),u++)
                      rangetotal+=delval(t+u);
                  rangeavg=rangetotal/(RANGE*2);
                  rangetotal=rangeerr=0;
              }
      }

```

-52-

```

5      for (u=0,u<=(RANGE-1),u++)
        {
          rangetotal+=delval(t-u);
          rangeerr+=rangetotal-((u+1)
            *rangeavg);
        }
      rangetotal=0;
      for (u=1,u<=RANGE,u++)
10      {
        rangetotal+=delval(t+u);
        rangeerr-=rangetotal-(u
          *rangeavg);
      }
15      delerr+rangeerr/(RANGE*2);
      delout=delval[i]-delerr/2;
      delta=delout-delnom;
      delvlt=delta/0.125000E-9;
      if(delvlt>3000)
        delvlt=3000;
20      if(delvlt<500)
        delvlt=500;
      voltodd[i/2+1]=delvlt;
    }
    else
25    {
      rangetotal=0;
      for (u=-(RANGE-1);u<=(RANGE),u++)
        rangetotal+=delval(t+u);
      rangeavg=rangetotal/(RANGE*2);
      rangetotal=rangeerr=0;
30      for (u=0,u<=(RANGE-1),u++)
        {
          rangetotal+=delval(t-u);
          rangeerr+=rangetotal-((u+1)
            *rangeavg);
        }
35      rangetotal=0;
      for (u=1,u<=RANGE,u++)
        {
          rangetotal+=delval(t+u);
          rangeerr-=rangetotal-(u
            *rangeavg);
        }
40      delerr=rangeerr/(RANGE*2);
      delout=delval[i]-delerr/2;
      delta=delout-delnom;
      delvlt=delta/0.125000E-9;
      if(delvlt>3000)
        delvlt=3000;
45      if(delvlt<500)
        delvlt=500;
50

```

-53-

```

    volteven[i/2]=delvlt;
    }

```

The above code estimates an interval error based on a number of surrounding intervals equal to 2*
 5 RANGE. It first computes an average interval value for the intervals within RANGE of the interval whose error is being computed. For each first trigger pattern within RANGE of the later trigger pattern of the second two trigger patterns which compose the
 10 interval of interest, the time distance between the first trigger pattern and the latter of the second two trigger patterns is computed and compared to the expected distance for local nominal intervals (rangeavg). An error contribution is obtained from
 15 each of these comparisons (rangeerr+=rangetotal-(u*rangeavg)). The average of these error contributions is the estimated error in the time of the latter of the second two trigger patterns. Some portion of this error is used to correct the
 20 subsequent write of the interval of interest.

SINGLE REVOLUTION TIMING PATTERN

Timing information in the form of equally spaced trigger patterns (which consist, for example, of one or more written magnetic transitions) at one radial
 25 position on a disk surface can be propagated over the entire disk radius without incurring a growth in the track to track alignment of the timing information. This process is further accomplished within a single revolution per servo track, thereby adding no
 30 additional time to the process of servowriting the disk drive. The importance of this advance is

-54-

critical for cases where the self-generation process occurs external to the disk drive and where additional rotations of the storage media directly impact the number of servowriter systems required.

5 For example, a system which required two revolutions of the rotating storage media to write a timing pattern and one additional revolution to move the recording head to the next servo track location would require 50% more servowriters than the technique
10 described above. This can represent a large capital cost, when the servowriter is external to the storage device.

One example of the process of self-propagation of a timing pattern is described in the steps below and is shown in FIG. 21. In this example, A is equal
15 to one half the interval T, but in general A can be any fraction of T.

- 20 1. A recording head is located on servo track location #0 and writes a series of odd number trigger patterns corresponding to every other sector on the disk surface, with an average interval size T.
2. The recording head is servo-positioned to servo track location #1.
- 25 3. The recording head triggers on each of the N odd numbered trigger patterns and writes an even number trigger pattern at a time A following each odd numbered trigger pattern. During this write sequence the
30 time interval between every two adjacent

-55-

odd numbered trigger patterns is measured and recorded in a computer memory as the values $T(n)$, where n runs from 1 to N .

- 5 3a. The interval $B'(n)$ is computed as $T(n) - A$.
- 3b. The deviation between $B'(n)$ and the nominal interval (e.g., A) is calculated and stored. This deviation is the random error for interval $B'(n)$, which is equal to $T(n) - 2A$.
- 10 4. The target intervals $B(n)$ are computed from the deviation and the nominal interval (A), given by $B(n) = F \cdot \{T(n) - 2A\} + A$, where F is described below.
- 15 5. The recording head is servo-positioned to the next servo track location.
- 20 6. The recording head triggers on each of the N even numbered trigger patterns and writes an odd number trigger pattern at a time $B(n)$ after each of the even numbered trigger pattern. During this write sequence, the time interval between every two adjacent even numbered trigger patterns is measured and recorded in a computer memory as the values $S(n)$.
- 25 6a. The interval $C'(n)$ is computed as $S(n) - B(n-1)$.

-56-

- 6b. The deviation between $C'(n)$ and the nominal interval A is calculated and stored. This deviation is the random error for interval $C'(n)$, which is equal to $S(n) - B(n-1) - A$.
- 5 7. The target intervals $C(n)$, are computed from the stored time intervals and the intervals $B(n)$ given by $C(n) = F \cdot \{S(n) - B(n-1) - A\} + A$.
- 10 8. The recording head is servo-positioned to the next servo track location.
- 15 9. The recording head triggers on each of the N odd numbered trigger patterns and writes an even numbered trigger pattern at a time $C(n)$ after each of the odd numbered trigger pattern. During this write sequence the time interval between every two adjacent odd numbered trigger patterns is measured and recorded in a computer memory as the values $T(n)$.
- 20 10. The intervals $B(n)$, are computed from the stored time intervals and the intervals $C(n)$ given by $B(n) = F \cdot \{T(n) - C(n)\} + \{1 - F\} \cdot A$.
- 25 11. Proceed to process step # 5 and repeat steps #5-#10 until the entire disk surface is filled with clock information.

In the above, F is a number from 0 to 1 which represents the weighting factor used to correct track

-57-

to track misalignment. For example when $F = 1$, the track to track misalignment error is minimized, but the absolute interval will deviate from the nominal value. When $F = 0$ the nominal interval size is maintained but track to track errors will grow unbounded.

It is understood that in addition to the above process to remove random error growth, one measures and corrects for all systematic delays due to both electronic and geometric effects, as described earlier. In addition, the technique previously described of "Improved Algorithm for Interval Control" can similarly be applied to this process.

In one embodiment, IC, as described above, is added to SD0 to produce the new value of SD, i.e., $SD = SD0 + IC$.

The propagation of servo patterns using this clock propagation process is shown in FIG. 22. The recording head is set to read mode and triggers on TP 0, which begins gating a pattern generator to write servo pattern #0. Then, the next recording head in the stack is selected and a second servo pattern #1 is written on surface #1 and repeated to N surfaces. The number N is limited by the time required to write each surface and the head switch time. At the end of the Nth surface, the head is switched to the first surface #0 in time to write the next sector TP 1.

The flow diagrams depicted herein are just exemplary. There may be many variations to these

-58-

diagrams or the steps (or operations) described therein without departing from the spirit of the invention. For instance, the steps may be performed in a differing order, or steps may be added, deleted
5 or modified. All of these variations are considered a part of the claimed invention.

Although preferred embodiments have been depicted and described in detail herein, it will be apparent to those skilled in the relevant art that
10 various modifications, additions, substitutions and the like can be made without departing from the spirit of the invention and these are therefore considered to be within the scope of the invention as defined in the following claims.